Pre-normative REsearch for Safe use of Liquid Hydrogen (PRESLHY)

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White Paper

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Key words

LH_2 safety, safe storage solution, technical solutions, hazard profiles, economic benefits

Publishable Short Summary

This white paper motivates the use of liquid hydrogen (LH_2) as a safe storage option for hydrogen and as a fuel. It introduces the involved technologies for production, storage and transport of LH_2. It compares the hazard profiles to compressed gaseous hydrogen and shows why LH_2 is the safer option. It explains the economic benefits of storing and transporting LH_2 in large scale or over long distance and to use it in weight critical applications like heavy duty transport. Finally, it provides recommendations for policy makers, who intend to raise the potential provided with LH_2.

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1 Introduction

Our energy system must transform into a more sustainable system with reduced impact on environment. Limiting global warming and managing an increasing energy demand of a growing world population require a fast shift towards circular economy schemes and preferential use of renewable energies. For a fast but successful and safe transformation broadly open exploitation of all technology options, flexible coupling of the different energy sectors and large-scale seasonal storage of renewable energy are required. This is perfectly provided with the energy carrier hydrogen and hydrogen technologies.

This white paper explains the advantages of using liquid hydrogen (LH_2), cryogenic hydrogen respectively, for scaling up hydrogen supply infrastructures and enabling weight critical mobility applications. It presents LH_2 as a safe and efficient storable version of hydrogen, describes the involved technologies and suggests actions in the political and scientific sphere for a safe introduction of the fuel of the future.

2 The growing hydrogen demand

For fast and thorough decarbonisation, as required by corresponding regulation, renewable energy has to be introduced in all applications, in all energy sectors at an increasing scale as soon as possible. Imported fossil fuels have to be replaced by “green” energy carriers, which may be harvested quite economically in remote places worldwide. Hydrogen as a versatile carbon-free, light-weighted energy carrier provides an attractive, almost unique solution to these challenges.

Existing use cases in the industry, where “grey” hydrogen is currently produced on-site with considerable CO_2 emissions, will serve as early entry points for green hydrogen. Integrating green hydrogen in refineries, ammonia or methanol production offers large scales for green hydrogen use and associated CO_2 reductions almost immediately. The industrial applications provide mature safety cultures and professional operations. However, new supply infrastructures are required.

Similar scales are implied with heat applications and with transport. Especially decarbonizing the transport sector turned out to be difficult within the last years. Whereas for light duty vehicles battery electric drive trains might be the most economic choice, weight and range critical transport, like heavy duty, water- and airborne transport are better addressed with hydrogen as a fuel.

3 The LH_2 solution for large-scale storage of hydrogen

As there are no natural sources for hydrogen, the life cycle of hydrogen always starts with the hydrogen production. Hydrogen is produced from either organic material (hydrocarbons) via reforming or pyrolysis or from water via electrolysis. In any of the production processes energy has to be invested, which is largely stored chemically in the product hydrogen. The typical production schemes deliver hydrogen in the gaseous state with a pressure below 3 MPa and with some characteristic impurities. With its very low density (about 0.09 kg/m^3 at standard conditions) the gas has to be either compressed or liquefied for achieving acceptable densities for storage or transport. The further processing also determines whether additional purification is needed.

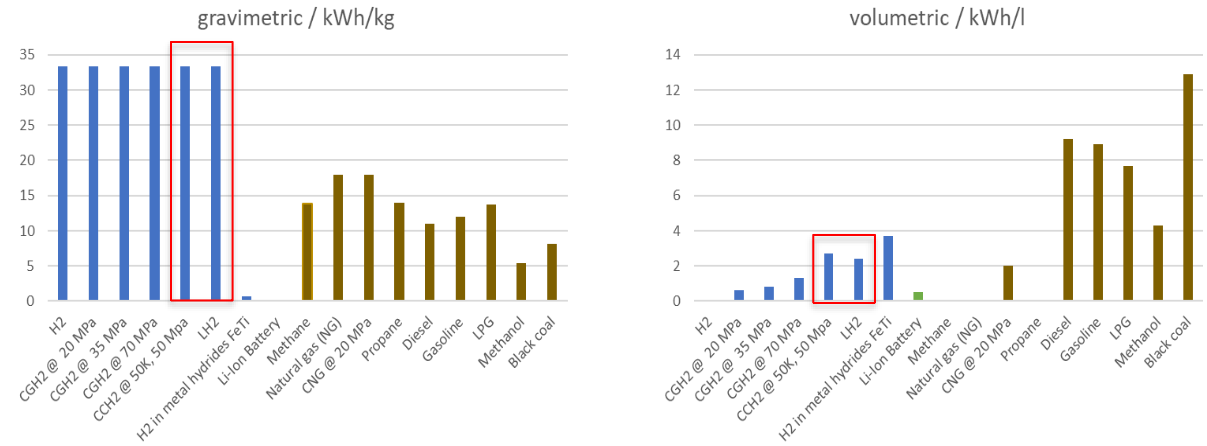


Figure 1:Energy density of hydrogen depending on temperature at different pressure levels compared to other energy carriers, CGH2 = compressed gaseous hydrogen, CCH2 = cryo-compressed hydrogen (left: gravimetric energy density; right: volumetric energy density)

The density of liquid hydrogen of 70 kg/m^3 is about 5 times larger than compressed hydrogen at 20 MPa and still considerably higher than compressed hydrogen at 70 MPa (38 kg/m^3). Figure 1 compares the gravimetric and volumetric energy density of liquid and cryo-compressed hydrogen to gaseous hydrogen and other energy carriers.

Accounting for the mass and volume of typical containers and comparing specific performance values of the storage system, clearly indicates that liquid hydrogen is the preferred option for energy and weight critical applications, like heavy-duty transport or aviation, for scaling up supply infrastructures and for mid- to long-distance transport of hydrogen itself.

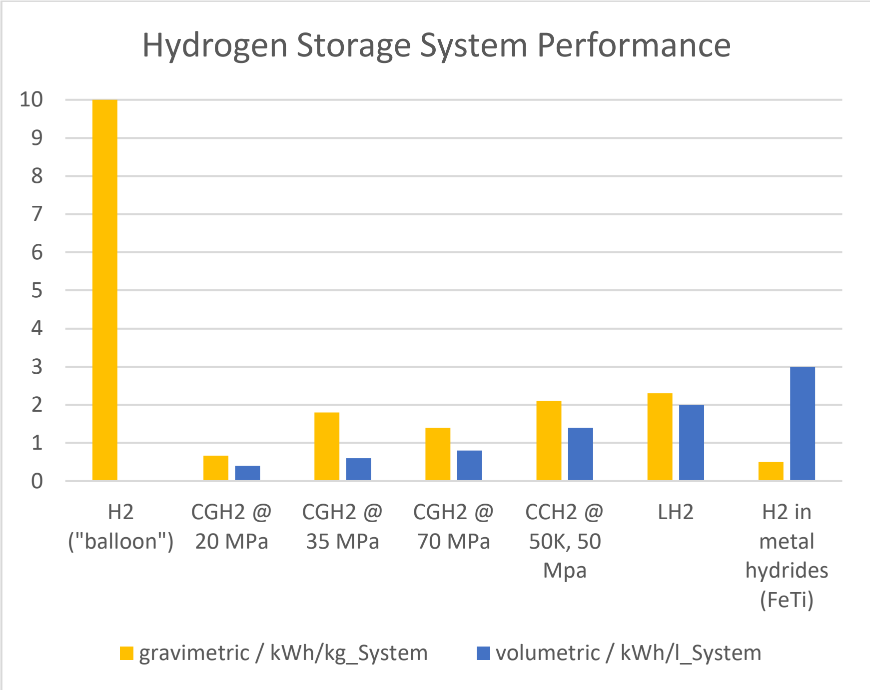


Figure 2: Hydrogen Storage System Performance

3.1 Hydrogen Liquefaction

Liquefaction of hydrogen is another energy intensive process as hydrogen has to be cooled to the boiling temperature of about 20 K. Table 1 compares the boiling temperature for a few prominent gases in a decreasing sequence.

Table 1: Normal boiling temperature of water, nitrogen, oxygen, hydrogen and helium

	H_2O	O_2	N_2	H_2	He
Boiling point	373 K	90 K	78 K	20 K	4 K

The principle available processes for cooling and achieving these very low temperatures are grouped into external cooling by a colder medium via a heat exchanger and internal cooling, where the medium itself undergoes thermodynamic changes associated with a temperature drop. The latter are split in processes where the media provides mechanical work in expansion turbines “expanders” or in piston machines and in isenthalpic throttling in Joule-Thomson valves.

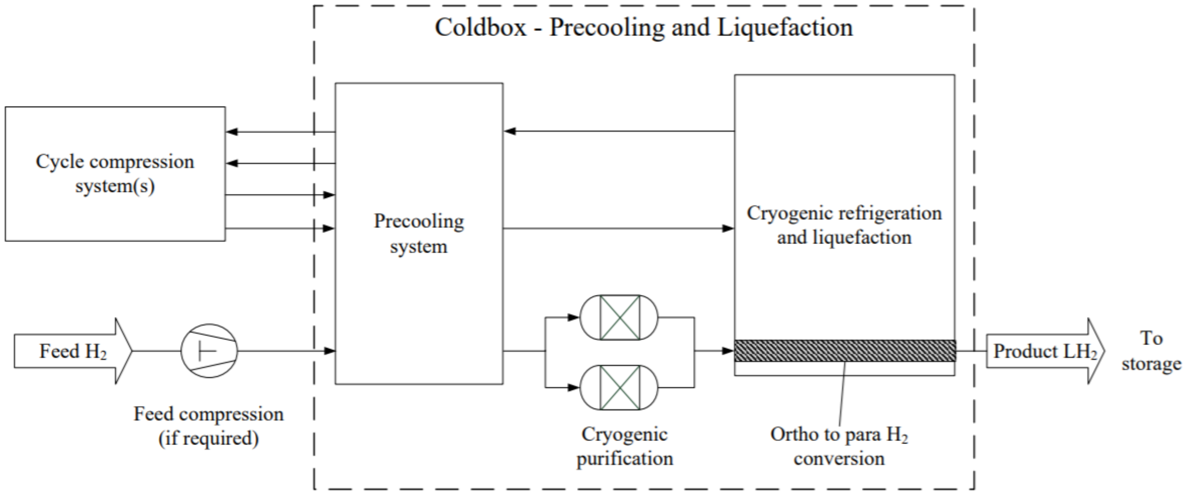


Figure 3: Simplified process flow diagram for hydrogen liquefaction (Source: Cardella, 2018)

Even in a perfect thermodynamic process at least 14.2 MJ (11.8% of the lower heat of combustion) are required to liquefy 1kg normal-hydrogen. This liquefaction exergy is larger than for other gases and includes removal of tangible heat (5.8 MJ/kg), latent heat (6.2 MJ/kg) and the heat released by ortho-para shift (2.2 MJ/kg).

The latter concerns the fact that there are actually two variants of hydrogen molecules, the ortho- and the para-hydrogen. In ortho-hydrogen the two nuclear spins of the two atoms composing the molecule are parallel, whereas in the para-hydrogen the spins are in opposite directions. This leads to different magnetic properties and to less energy content in the para-hydrogen molecule. At normal conditions, hydrogen consists of 75% ortho- and 25% para-hydrogen ("normal hydrogen") and at low temperatures close to the boiling point predominantly para-hydrogen. As the ortho-para shift releases a considerable amount of energy, it is important to include this step in the production and product specification of LH_2.

The commonly applied method in large-scale liquefaction plants is the Claude process combined with liquid nitrogen LN_2 pre-cooling, where the necessary refrigeration is provided in four main steps (Krasae-in, 2010):

1. Compression of hydrogen gas with removal of compression heat;
2. Precooling with liquid nitrogen (> 80 K);
3. Cooling of a part of the hydrogen in an expansion machine "expander" (> 30 K);
4. Expanding of the residual hydrogen in a Joule-Thomson valve (20 K).

Joule-Thomson expansion is applied for the final step to avoid two-phase flow in the expander.

Currently, established liquefaction technology requires in the order of 40 MJ/kg – what is 33% of the lower heat of combustion of 120 MJ/kg and an exergy efficiency – defined as ratio of liquefaction exergy over actually required energy – of about 36%. Feasibility studies, as performed in the IDEALHY project (Stolzenburg, 2013), showed a potential to reduce this to 22 MJ, corresponding to an efficiency of about 65%. Improvements in efficiency are expected with the development of new materials, better heat exchangers and new compression/expansion technology. An interesting but still immature technology is magnetic refrigeration, where the entropy difference and the adiabatic temperature change upon application or removal of magnetic fields is utilised. However, this process is deemed to be used for the rather low temperatures and suitable materials are still lacking.

The current worldwide production capacity in about 35 installations is approximately 350 t per day. Northern America has with 85% the largest share. In Europe there are currently only 3 large liquefaction plants (Aasadnia, 2018).

3.2 Storage of LH2

Similar to compressed storage, there are two main classes of LH_2 storage vessels. There are cryostats for stationary applications and for transport. Representatives of both classes are shown in Figure 4 and Figure 5.

Figure 4: 3800 m^3 LH_2 Storage at Kennedy Space Flight Center in Florida (Source NASA)

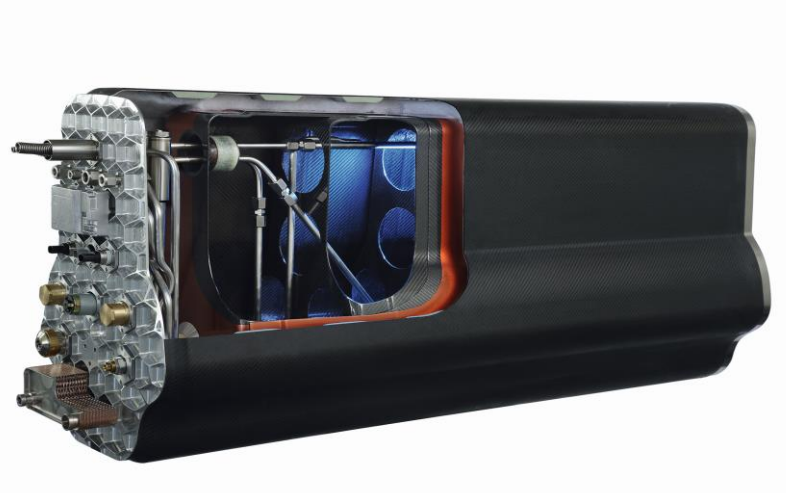


Figure 5: Cross-sectional model of a LH_2 lightweight formtank with integrated auxiliary system for automotive application (Source: BMW AG)

Cryogenic vessels have been commonly used for more than 40 years for the storage and transportation of liquefied gases including liquid hydrogen. In order to manage storage at -253°C, for large inventories (> 100 m^3 volume) double-walled vacuum-insulated pressure tanks are used. Such vessels consist of an inner pressure vessel and an external protective jacket. The volume between inner vessel and jacket is filled with compressed perlite under vacuum. Perlite is an inorganic amorphous volcanic glass that represents a good trade-off between cost and insulation properties. For smaller cryostats (< 100 m^3) a multi-layer insulation MLI is used instead. This insulation is composed of several layers of a metallic coated plastic sheet, separated by a grid like spacer. The heat absorption for the small automotive LH_2 storage tanks with an internal volume of about 100 l, like the one shown in Figure 5, is thus reduced to about 1W. This heat input leads to evaporation and via a pressure limiting valve to the boil-off of the evaporated cold gases. The boil-off corresponds to a loss of 1.5% of the stored energy per day for small cryostats. The typical stored mass of about 7kg will be lost in 2 months if the car was not used in this phase.

The following boil-off management may reduce these losses or at least reduce the associated risk with released hydrogen by:

- cold combustion with air in catalytic recombiners,
- storing the boil-off gases in metal hydrides or other adsorbers,
- re-cycling in a re-liquefaction process,
- direct energetic use, in a fuel cell for instance.

Of course, the involved temperatures are demanding not only regarding the design of the actual storage but also regarding the compatibility of all connected technologies, like measurement techniques, armatures, valves, and piping. Also fuel cells actually require higher temperature of the feed hydrogen. However, the cooling power of the extracted gases might be used also for cooling purposes, which represent in particular for low temperature fuel cells a challenge.

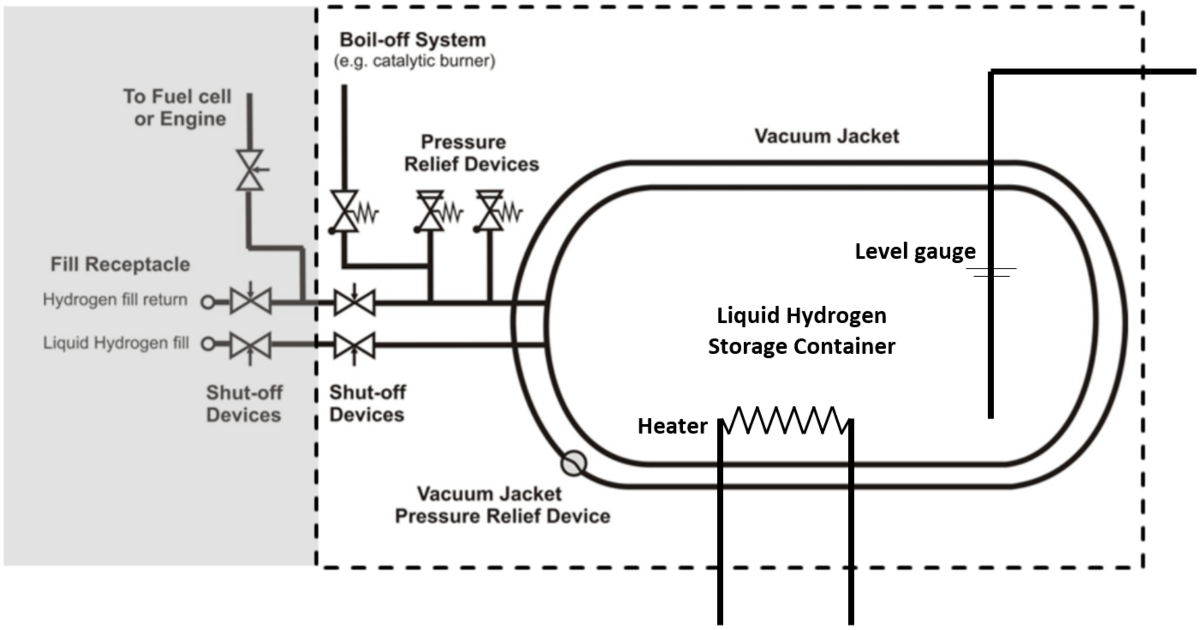


Figure 6: Liquid Hydrogen Storage System LHSS (based on: UN ECE GTR13)

So, the typical liquid hydrogen storage system, as shown in Figure 6, consists of the following components:

- insulated liquefied hydrogen storage container(s);
- shut off devices(s);

- a boil-off system;
- Pressure Relief Devices (PRDs);
- a level gauge for measuring the filling level,
- a heater, either electric or heat exchanger air for higher extraction rates, and
- interconnecting piping (if any) and fittings between the above components.

3.3 Transport of LH_2

Liquid hydrogen may be transported for short distances in pipelines, for larger distances in storage systems as described in the previous chapter.

Cryogenic liquid hydrogen trailers can carry up to 5 000 kg of hydrogen and operate up to 1.2 MPa (with a certain distance from critical pressure). Hydrogen boil-off can occur during transport despite the super-insulated design of these tankers, potentially in the order of 0.5% per day. Hydrogen boil-off up to roughly 5% also occurs when unloading the liquid hydrogen on delivery.

The LH_2 trailers are insulated using a vacuum super insulation, similar as described for the storage containers. This thermal insulation system typically includes:

- A double-shell insulation space (interspace) where static or dynamic (for large storage) high vacuum is limiting heat transfer by conduction and convection;
- A blanket of alternate layers of highly reflecting shields (Aluminium for instance) and insulating spacers (Lydall for instance) to prevent heat transfer by radiation as well as conduction between shields;
- An adsorbent (molecular sieve) placed in the vacuum space in order to achieve an adequate level of vacuum at low temperature by adsorption of residual gases and moisture.

Figure 7: Trailer transport of liquid hydrogen

Pipes for transferring cryogenic liquid hydrogen provide relatively large specific surface and therefore must be insulated even more carefully. Similar concepts as for storing LH_2 in cryostats are applied. A prototypical transfer pipe for LH_2 therefore consists of at least two concentric tubes combined with superinsulation material in the vacuum insulated. There are rigid or flexible variants (see Figure 8).

Figure 8: CRYOFLEX® Transfer Lines for LH_2 by Nexans

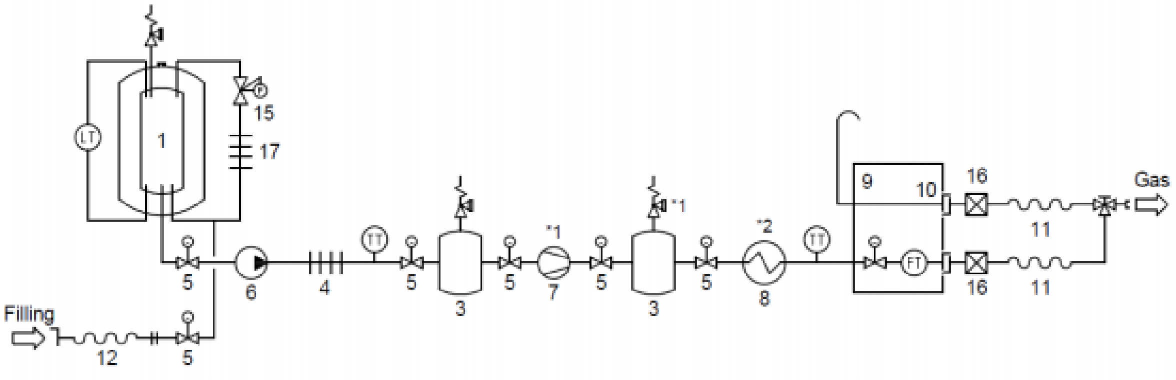
Because of the relatively high heat ingress such LH_2 pipelines are usually limited in length. Typical use of flexible lines is for transfer from a trailer to a stationary storage or for filling lines at a refuelling station. Larger set-ups are typically used for filling rocket tanks at space flight centers, like the one of NASA in Florida, USA.

3.4 LH_2 based refuelling stations

Basically, a LH_2-based refuelling station consists of:

- a vertical or horizontal LH_2 tank. Tanks at the utilisation site are usually smaller with capacities from 100 to 2 500 kg for vertical tanks and up to 5 000 kg for horizontal tanks. Usually, the maximum operating pressure is 1.2 MPa;
- an insulated process line from the bottom of the storage to the LH_2 pump (reciprocating or submerged) pumping LH_2 from the storage tank to the atmospheric vaporizer. This device allows to pump LH_2 up to 100 MPa.
- a heater (hot oil, electric or atmospheric heat exchange) in order to heat up hydrogen at 100 MPa;
- 100 MPa gaseous buffers (few m^3). These buffers are generally bundles of type I or II metallic cylinders or long metallic tubes; and
- all the other parts (dispenser, filling hose, …) of the refuelling station are similar to classical gaseous refuelling station.

The LH_2 is delivered by a LH_2 trailer truck. The LH_2 trailer has a 40 m^3 horizontal tank operating between 0.1 and 1.2 MPa. The connection between the truck and the stationary storage at the refuelling station is done by a flexible transfer line. The transfer is performed without a pump. Instead a small vaporizer, a heater respectively, is present on the trailer to pressurise truck tank and to allow the transfer of liquid H_2 in the stationary vertical storage by the generated pressure difference.



1. liquid hydrogen storage unit	8. chiller	15. pressure regulator
2. gaseous hydrogen storage unit	9. dispenser	16. breakaway coupling
3. intermediate gas storage	10. safety valve	17. pressure build-up evaporator
4. evaporator	11. delivery hose	
5. emergency shutdown system	12. off-loading hose	LT level sensor
6. pump	13. fill	FT flow sensor
7. compressor	14. purifier	TT temperature sensor

Figure 9: Process flow of a LH_2-based hydrogen refuelling station

Figure 10: View of a LH_2-based hydrogen refuelling station (90 MPa - 100 kg/d; source: Linde).

4 Safety aspects

Hydrogen is not more or less dangerous compared to other fuels, it is different and doesn't bring more safety concerns if it is dealt with professionally. The safe handling of gaseous and liquid hydrogen is the established practice in the industrial environment, including the experience gathered within the scope of the international and national space programs, where liquid hydrogen is produced, transported, stored and used in large amounts. However, this experience is only partially applicable to new applications of hydrogen as an energy carrier in non-industrial settings.

There are technological and safety-related pros and cons of the use of hydrogen in gaseous or liquid form for different applications.

Many safety-relevant characteristics are shared by both compressed and liquefied hydrogen. Hydrogen is highly diffusive and might leak, e.g. via imperfect fittings, and mix with air forming flammable mixtures in comparatively wide flammability range. Flammable cloud after LH_2 release or spillage is "visible" as the boundary of condensed atmospheric water vapour is practically coincides with the lower flammability limit (LFL) of 4% by volume of hydrogen in air. Due to higher density (low temperature) and water vapour condensation, the release of LH_2 is less buoyant at the initial stage but in a comparatively short time the main safety asses of hydrogen, i.e. buoyancy, takes over and "visualised" by water vapour flammable cloud raises and disperses in the open atmosphere below LFL. Hydrogen has the lowest minimum ignition energy (MIE) and it can be expected that practically any released and mixed with air hydrogen may be easily ignited. However, there was no ignition observed in a series of large-scale experiments performed by NASA in 80th of last century. Because of the missing carbon atoms the reaction kinetics of hydrogen-air combustion yields relatively fast chemical reaction and flame propagation which have a strong tendency to accelerate because of instabilities rooted in the low density, high diffusivity and low viscosity of hydrogen. Lower temperatures reduce laminar burning velocity but, as observed in PRESLHY project, can reduce run-up distance for the transition to detonation due to instabilities, including that generated by flame front itself. On the other hand, due to the absence of carbon, the radiative heat flux from hydrogen flames is much less compared to hydrocarbons. Some materials, in particular high strength steels, are subject to hydrogen embrittlement.

It is important to understand how hydrogen safety characteristics are affected by the storage option, i.e. by storing hydrogen in either compressed gaseous or liquefied form. Safety characteristics of cryogenic liquid hydrogen can be different from gaseous hydrogen and yet to be understood further.

4.1 Storage and accidental releases

The compressed hydrogen in a pressure vessel up to around 100 MPa, contains considerable mechanical energy compared to pressures of LH_2 stored at pressures of an order of 1 MPa. However, it is not yet understood if overpressure generated by LH_2 BLEVE is less hazardous for life and property. Indeed, if the expansion of liquid to gaseous hydrogen (increase in volume by 847 times) happens fast enough then the generated pressure wave after storage tank rupture in a fire could have serious safety consequences that would be aggravated by the contribution of chemical energy of combustion to the blast wave strength.

High-pressure releases, sometimes entraining small fragments from the fracture surface itself, might impact on other components, or hurt persons. The high momentum gas release induces strong recoil force on the releasing pipe or container. The rupture in a fire of compressed hydrogen vessel at 35 MPa and 70 litres under the vehicle (the largest "projectile") translated it by 22 m.

LH_2 is usually stored at moderate pressures, well below the critical pressure of 1.3 MPa. However, the extremely low temperatures might embrittle non-suitable materials and lead to thermal stresses. If not shielded carefully the cold surfaces might lead to condensation of highly reactive oxygen or cryo burns when human beings come into contact with these cold surfaces or accidentally released cryogenic hydrogen.

The increase in density of low temperature cryogenic, liquid hydrogen leads to the elimination at the initial stage of release of the otherwise strong buoyant forces acting on warm hydrogen released into the atmosphere. Up to 30 K hydrogen is heavier air at ambient temperature. The mixing with ambient temperature air quickly leads to warming up on one side and to a dilution on the other. On the other side, the flammable envelope created by LH_2 release is easily identified by the visible clouds formed when the released cryogenic hydrogen condenses the ambient humidity. Flammable envelope and the boundary of the visible cloud coincide quite well.

PRESLHY research demonstrated that concentration decay in momentum-dominated hydrogen jets at ambient and cryogenic temperatures obey the similarity law currently widely used in hydrogen safety engineering.

4.2 Ignition

From more than 500 single tests performed in the PRESLHY project and from other accessible databases (Kreiser, 1994) it may be derived that cryogenic hydrogen is much less probable to ignite than ambient warm hydrogen released from high pressure reservoirs.

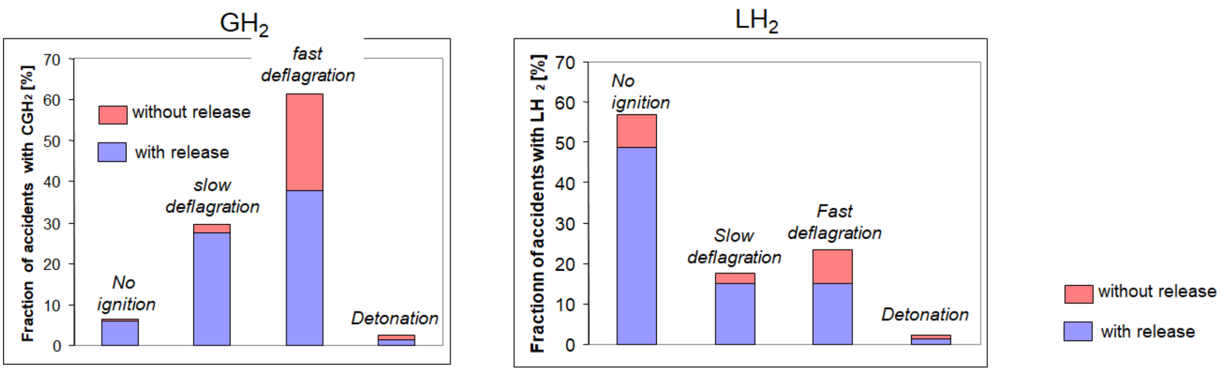


Figure 11: Fraction of accidents without ignition, slow and fast deflagration and with detonation in the full sequence of events (Kreiser,1994)

Without ignition, there is no further escalation into combustion or explosion with more serious thermal and blast loads.

4.3 Combustion, Explosions, Fireballs

There are at least two competing effects in the combustion of cryogenic hydrogen-air mixtures. Compared to warm hydrogen the density of the cold hydrogen-air mixtures might be up to 4 times higher. This means that almost 4 times more chemical energy is available in the same volume. On the other hand, the low temperature slows down the flame propagation processes seriously leading to increase of flame front area and thus to the increase of the burning rate. This lead to slightly more critical scenarios with liquid hydrogen in closed and obstructed rooms and the opposite for the open space scenarios. This is again reflected in the statistics (see Figure 11) and was confirmed in combustion tube experiments performed in the PRESLHY project.

Phenomena like boiling liquid expanding vapour explosions (BLEVE) or rapid phase transition (RPT), observed for liquid natural gas (LNG) and liquid petroleum gas (LPG) are not yet investigated sufficiently for LH_2 due to the need to use comparatively large amounts of LH_2 that implies the relatively high cost of experiments and their safety arrangements. This would require an investment of financial and intellectual resources.

There is no or little difference expected in a fireball size after hydrogen tank rupture in a fire. The maximum size is proportional to stored mass in power 1/3 and expected to be large for LH_2.

Hazard distances from hydrogen jet flame originating from high-pressure storage and storage at cryogenic temperature obey the same dimensionless flame length correlation that is in use by hydrogen safety engineers.

The direct comparison of LH_2 with compressed gaseous hydrogen shows some disadvantages stemming from the wider spreading of hydrogen on the ground level and possible formation of oxygen-enriched zones. However, this drawback is “compensated” by the benefits associated with the reduced ignition propensity and generally slowed down reactivity at the low temperatures.

A profound understanding of the associated safety-critical phenomena, proper safety planning, monitoring of operation procedures and overall safety management and generally pro-active new safety culture of hydrogen use in the public domain is required to deploy hydrogen as an energy carrier safely. Figure 12 summarises those findings in a properties/hazards profile.

The understanding of LH_2 safety-related phenomena investigated in PRESLHY paves the way to the development of scientifically underpinned innovative safety strategies and breakthrough engineering solutions in forthcoming research of hydrogen technologies with the use of LH_2.

In summary, the overall hazards and associated risk potential of LH_2 is comparable to compressed gaseous hydrogen. However, the knowledge of the difference in safety characteristics of gaseous and liquid hydrogen and the fundamentals of hydrogen safety engineering makes it easy to develop a reliable hydrogen safety system providing a similar level of safety provisions for people and the built environment.

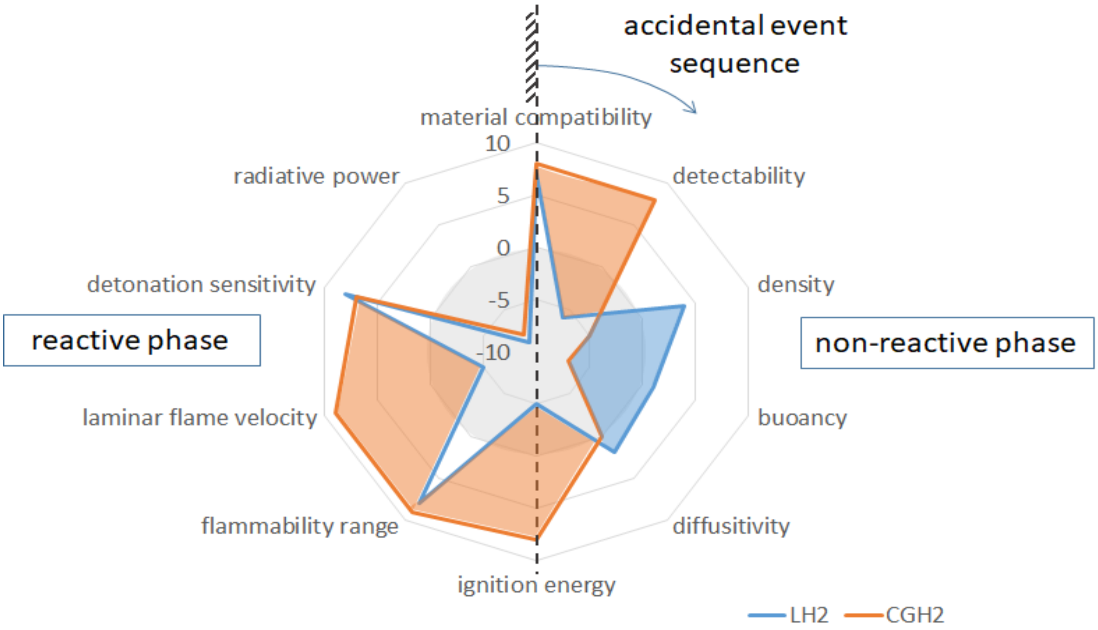


Figure 12: Comparison of safety critical properties of liquid hydrogen and compressed gaseous hydrogen, along a prototypical accident sequence of events

5 Economical aspects and benefits

The energy required for liquefaction is only slightly higher as for compression to 70 MPa (40 vs 30 MJ/kg). With the potential to reduce this energy requirements by about 50% within the next decade and the additional use of the cooling capacity LH_2 will be competitive even for middle sized installations.

The relative high density of LH_2 reduces the required storage volume. This allows for a more flexible refuelling stations design with considerably smaller land use, for instance. Together with the low pressures typically involved and the relatively low costs for thermal insulation, the overall specific hydrogen storage costs are reduced with LH_2 substantially.

Similarly the increased density and reduced pressure affect the economy of batch transport. The investment costs for transport equipment and the operational costs are seriously reduced as shown in

Figure 13 (Reddi, 2015). One LH_2 trailer suffices to transport the same hydrogen inventory as at least 5 and up to 15 trailers with compressed gaseous hydrogen. Additionally, the LH_2 road trailers typically come with a total weight of about 25 tons, whereas the gaseous trailers must utilise the maximum permissible total weight of 40 t on European highways. Obviously, this reduces the load on roads and on traffic, respectively transport infrastructure in general.

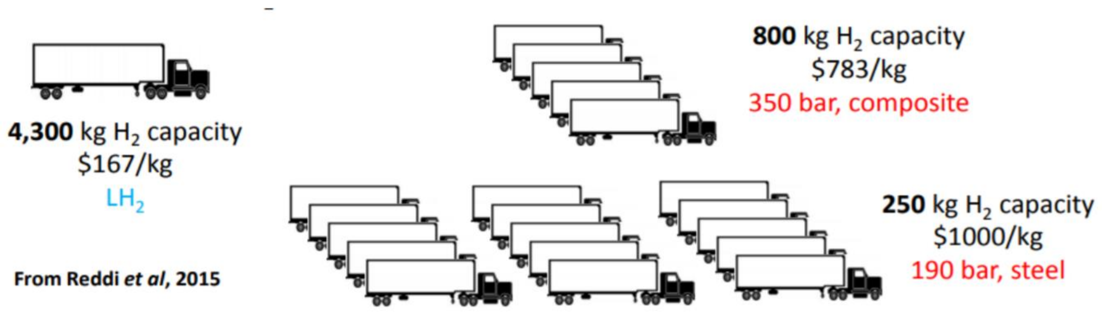


Figure 13: Capacities and investment costs for LH_2 and CGH2 trailer transport (Reddi, 2015)

With respect to refuelling, there are several further striking advantages of LH_2 based refuelling stations. Pumping LH_2 to the required pressures of about and above 70 MPa is much more energy efficient than compressing highly compressible warm gases. The standard 70 MPa fillings (SAE J2601) require a pre-cooling of the compressed hydrogen to down to -40°C. The energy requirements for this pre-cooling are relatively high at the currently operational gas based refuelling stations, whereas this pre-cooling is implicitly included, comes for free in liquid based refuelling stations. Thus, the invested efforts for liquefaction are recovered to an essential degree herewith.

This cooling capacity is potentially useful also for other purposes. The steadily growing demand for cooling power in many industries and warehouses might be addressed with the cryogenic hydrogen. This becomes particularly interesting, if multiple usage is considered.

For instance, the cooling of high temperature superconductors with LH_2 is an innovative solution, very promising in many aspects. The lossless transfer of electricity would be coupled to the transport of chemical and thermal energy. Thus, these cables could be considered key elements of the sector coupling. Moreover, such high power superconducting electricity lines require only small cross-section and non-critical materials and therefore come at relatively low specific costs. Compared to other prominent cooling media (liquid helium LHe or liquid nitrogen LN2) for superconductors, LH_2 provides better cooling capacities and lower costs in comparison to LHe. Finally, LH_2 cooled superconductors are very light and therefore are best suited for the future electric flying.

In the research and development project icefuel (Markowz, 2010) a flexible plastic pipe for such a combined transport of LH_2 and electricity via high temperature superconductor was tested, see Figure 14.

Figure 14: icefuel cable sample (outer diameter ~40mm; max. chemical transport capacity 100-200 kW_{LHV}; source: LEONI)

6 Policy and regulatory implications

6.1 Background

International governments have entered into climate change agreements that will require significant reduction in the usage of fossil fuels to reduce CO2 production, halt global warming and associated issues including loss of land mass due to sea level rises, widespread forest fires, etc. The chemical energy storage hydrogen burns without producing CO2 and so is a natural choice to replace fossil fuels, e.g. natural gas, gasoline, LPG, etc, for transport and heating applications. This provides the key policy requirement to increase the use of H2 as a flexible carbon-free energy storage and alternative fuel. There is a need for rapid development and widespread roll out of new hydrogen-based technologies.

Liquid hydrogen LH2 with its high density, purity and safety characteristics will be needed as part of this global change in technology. This gathering of momentum leads to the policy need to provide suitable frameworks and boundary conditions for production, storage and use solutions that are technically viable, energy efficient and safe for humans and the environment. The development of a comprehensive set of standards for the safe design and operation of liquid hydrogen facilities for its whole lifecycle is pivotal to the safety of this transition. In order for the hydrogen market to grow, harmonised standards and guidance are required by developers, design engineers, manufacturers and installers; in addition to synchronised policies for regulatory authorities/ bodies to ensure consistency.

Policy and regulation will need to focus on the protection of life, infrastructure (property/equipment) as well as the environment. Of utmost priority would be for regulators to ensure that risks to human life are as low as reasonably practicable (ALARP), and this would include general public/ customers, site workers, as well as emergency responders. Examples of LH2 operations include bulk transport, refuelling stations, bunkering facilities for ships and airport services. Producing, storage and operating companies should also endeavour to ensure risks of damaging infrastructure/ equipment including escalation and domino effects are ALARP, as well as reduce risks of reputational and financial loss. Regulators, through the help of local environmental authorities should also ensure that impact to the natural environment is minimised.

6.2 Regulation and Standardisation

From a safety perspective, existing key regulatory controls in Europe include the European Seveso III Directive for production and storage of fuels and international agreements on the carriage of dangerous goods (relevant to the supply of hydrogen). These are underpinned by European and international standards for the design and operation of the infrastructure.

In regulation hydrogen use is not a new concept (Joyce and Strachan, 2020); a range of international standards apply to hydrogen, including but not limited to, those developed by the International Standards Organisation (ISO) ISO/TC 197 Hydrogen Technologies; the International Electrotechnical Commission (IEC); and the European Industrial Gases Association (EIGA). In fact, in July 2020, the European Commission (EC) released its own hydrogen strategy “EU Strategy”, which is divided into three phases of development (2020-2050) of the European hydrogen economy:

The EU Strategy is a pivotal part of the ‘European Green Deal’, which aims to achieve climate neutrality in Europe by 2050. In July 2020, EU leaders collectively approved a €1.8 trillion package geared towards boosting EU economic recovery post-COVID-19, with the Green Deal now seen as a key element of the recovery strategy. The strategy aims are to be achieved through decarbonisation of existing hydrogen production for its current applications in the various sectors and promote and expand it into new sectors such as steel-making, transport (trucks, rail, aviation, etc.) and some maritime applications; with increasing hydrogen demand being met through optimisation of its production, use and transport. The last phase of the strategy involves deployment at large-scale to reach all sectors, including those difficult to decarbonise. It is worth noting that the scope of the above strategy extends beyond cryogenic hydrogen.

Initiatives such as the implementation of the EU's Fuel Cells and Hydrogen Joint Undertaking (FCH JU) industry-led Regulations, Codes and Standards Strategy Coordination Group (RCS SCG) try to identify the gaps and needs for additional pre-normative research or Regulation, Codes and Standards (RCS) in the field of hydrogen including cryogenic hydrogen. Within Europe, the European Hydrogen Safety Panel (EHSP) was established in 2017 to assist the FCH JU both at programme and at project level to ensure that hydrogen safety is adequately managed, and to promote and disseminate hydrogen safety culture within as well as outside of the FCH JU programme. The EHSP is composed of a multidisciplinary pool of safety experts grouped in ad-hoc working groups for different workstrands. In addition to this, the FCH JU HyLaw project (Floristean and Brahy, 2019, Floristean et al, 2019 and Hayter, 2018) brings together 23 partners including 18 Member States (from Austria, Belgium, Bulgaria, Denmark, Finland, France, Germany, Hungary, Italy, Latvia, Norway, Poland, Romania, Spain, Sweden, Portugal and the Netherlands plus the United Kingdom) aimed at the removal of legal barriers to the deployment of fuel cells and hydrogen applications. This is aimed to boost the market uptake of hydrogen technologies by providing market developers with a clear view of the applicable regulations whilst calling the attention of policy makers on legal barriers to be removed, under eight main application areas such as production, storage and transport (including LH2), use as fuel, use in vehicles including marine, electricity grid issues, gas grid issues and stationary power.

Under the Seveso III Directive, H2 is in scope at thresholds of 5 tonnes for Lower-Tier (LT) and 50 tonnes for Upper-Tier (UT). Most production and storage facilities will therefore be in scope of Seveso III, and most filling stations may become LT sites. UT sites are required to produce a safety report/case to be submitted to the relevant health & safety regulator. This will provide a mechanism for regulatory control but there may need to be considerations at EU level as to whether the resource requirements of the regime for regulators and operators would be too onerous once a comprehensive set of standards is available, particularly for refuelling/ filling stations and other facilities with relatively low inventory. Under Seveso III, there are strong requirements for the provision of public information, including a broader duty to manage domino effects; as well as a duty for lower-tier establishments to provide public information. There are provisions for electronic access to up-to-date public information.

In view of the expected roll-out of hydrogen refuelling stations in the coming years the Energy and Hydrogen Alliance (EHA), in collaboration with EIGA, submitted a strong suggestion to double the threshold for onsite hydrogen storage from 5 to 10 tonnes (H2 EuroOrg, 2021). This request was denied in the final Commission's proposal, as the number of larger hydrogen refuelling stations in operation across the EU is expected to be still limited in the coming years. The Commission however refers to the possibility of using "delegated acts" to change non-essential parts of the legislation if deemed necessary at a later stage. The EHA is currently considering lobbying Parliament and the Council to include the doubling of the threshold to avoid amending the legislation at a later stage.

There may be a need for new regulations and policy to be established in the area of hydrogen refuelling stations (including multi-fuel configurations), though LH2 shares many of the hazards from compressed LNG. A number of FCH JU projects expect to fill some of the knowledge gaps and output some recommendations for development or modification of regulation, codes and standards.

6.3 LH2 specific safety aspects

As a cryogenic liquid, hydrogen is stored as a liquid below -253°C and therefore, consideration should be given to cold burns, oxygen-enriched atmospheres, and the way in which a liquid spill may develop into a flammable cloud (Pritchard et al, 2010). It should be appreciated that the vapour produced by a liquid spill will not initially be buoyant due to its low temperature. In addition, liquid hydrogen is always accompanied by a certain amount of gaseous hydrogen, hence it is necessary to consider both the properties of liquid and gaseous hydrogen together.

UNECE (2013a) para 122 states that, "In order to maintain the hydrogen in the liquid state, the container needs to be well insulated, including use of a vacuum jacket that surrounds the storage container. Generally accepted rules or standards are advised for use in the proper design of the storage container and the vacuum jacket." Loss of containment from liquefied hydrogen storage can be catastrophic within enclosed steel structures due to a number of reasons, such as but not limited to: immediate loss of toughness and embrittlement of carbon steel including weld metals; H2 vapours can remain denser than air for extended periods; low ignition energy, wide flammability/ explosibility limits; high flame velocities which may transition to detonation with shockwave; the very low temperature release can lead to liquefaction and freezing of inert gas and constituents of air near the leakage and O2-enriched atmosphere/ air will further increase hydrogen reactivity. Hydrogen fires also have low flame visibility.

Currently, for extended distances, LH2 is transported in super-insulated, cryogenic tankers. After liquefaction, the liquefied hydrogen is dispensed to delivery tankers and transported to distribution sites where it is vaporized to a high-pressure gaseous product for dispensing. Because a liquid tanker can hold a much larger mass of hydrogen than a gaseous tube trailer can, transporting liquid hydrogen is more economical than in gaseous form. However, challenges exist with liquid transportation include the potential for boil-off during delivery. In terms of transport, whilst there are currently no specific limits in quantity and pressure to H2 in transportable H2 cylinders (for example in the UK) – provided that the cylinder and pressure regulator valve meets required pressure Directive standards / ISO standards and are CE-marked. In the UK, the Pressure Equipment (Safety) Regulations do apply to the design, manufacture, conformity assessment and periodic reassessment of transportable cylinders, tubes, cryogenic vessels and tanks for transporting gases; it also covers associated valves and includes both refillable and non-refillable cylinders. It applies to existing equipment as well as new equipment introduced since the Pressure Equipment Directive which applies to the design, manufacture and conformity assessment of pressure equipment with allowable pressure greater than 0.5 bar above atmospheric pressure for the maximum/ minimum temperatures for which the equipment is designed for gases, liquids and vapours. Existing equipment is checked for compliance during annual periodic assessments. Aspects of the design, production and testing of the equipment are the subject of a large number of harmonized standards.

The UK Transportable Pressure Equipment Regulations 2009 (formerly TPED) have been fully updated and the legislation effectively now implements the requirements of the European agreement concerning the carriage of dangerous goods (ADR); equipment previously made to those standards and specifications may continue to be used in Great Britain as long as it is subject to a proper test and inspection regime – for which the Department for Transport (DfT) is the UK "Competent Authority“ and the Vehicle Certification Agency (VCA) administers the system for the appointment of bodies for the conformity assessment and periodic inspection of Transportable Pressure Equipment.

In 2019, EIGA released its Doc 06/19 publication (EIGA, 2019) - intended as guidance for companies directly associated with the installation of LH2 storage at the user's premises and the distribution of liquid hydrogen by road, rail and sea transport, but excludes portable containers such as pallet tanks and liquid cylinders. The guidance was divided into four main areas: H2 (including LH2) properties and hazards; customer installations (production, storage, layout, design, access, testing, commissioning, decommissioning, operations, maintenance); LH2 transport and distribution (road, rail and inland waterways and sea); and personnel training and protection (gas supplier, customers, Permit to Work). Several other principal regulations exist in Europe to cover hydrogen facilities (not just LH2): these include, but are not limited to, those regulations which arise from the various national legislations passed to implement the ATEX Directives and the Pressure Equipment Directive.

Operators/ dutyholders of LH2 installations should be obligated to undertake the necessary risk assessments to identify the hazards and consider and/ or implement the necessary risk reduction measures to eliminate, control or mitigate their effects. This would need to be regulated and monitored by the relevant health and safety regulatory body in each country. The risk assessment should include all hazards associated with the whole lifecycle of the LH2 application, so could span a number of operators/ dutyholders - including new ones who have just come into scope; as well as regulatory bodies.

The benefits of LH2 over GH2 would need to be demonstrated in the context of these policy requirements. Over longer distances it is usually more cost-effective to transport hydrogen in liquid form, since a liquid hydrogen tank can hold substantially more hydrogen than a pressurized gas tank. Whilst PRESLHY has indicated that liquefied hydrogen is the better option compared to compressed gaseous hydrogen and offers economic benefits in bulk storage and transportation, it does still present some technical challenges which will need addressing, as well as regulatory and policy implications.

6.4 Enabling function and remaining challenges

As such, it is pertinent that policy and regulation is to function as an enabler, including designing market rules for the deployment of hydrogen; removing barriers for efficient hydrogen infrastructure development or repurposing; and ensuring access to liquid markets for hydrogen producers and customers and the integrity of the internal gas market, through the review and development of legislation, codes and standards to allow consistent application by member countries. This allows all stakeholders to place safety as priority in a systematic, structured and robust manner. Winning the trust of the public trust in the safety of liquefied cryogenic hydrogen is pivotal to building the public confidence needed for widespread uptake.

HSE Research Report RR769 (Pritchard & Rattigan, 2010) presents the main challenges of applications involving liquid hydrogen. The work presented some suggestions of potential research areas - these are reproduced in bullet points below. A number of the recommended research areas have been addressed within the PRESLHY project itself.

- Applications involving liquid hydrogen present additional fire and explosion hazards to those arising from use in gaseous form, which need to be fully appreciated if levels of safety comparable to those from conventional fuels such as petrol and liquefied petroleum gas are to be achieved.

- The requirements in the current regulatory framework are adequate for controlling the fire and explosion hazards from the transport and storage of liquid hydrogen. Where safety issues arise they are in the understanding of liquid hydrogen behaviour and the lack of standards and guidance to assess the hazards, ensure equipment is fit for purpose and to demonstrate compliance with the regulations.
- The consequences of an accidental spillage or leak of liquid hydrogen are poorly understood, particularly the initial stages of pool spread and vaporisation. A better understanding of this initial phase together with more experimental data on the dispersion phase are required if reliable models for predicting the consequences are to be developed and validated. There is currently lots of research work which is being funded by the EU, as well as commercially.
- The separation distances given in current standards and guidance on hydrogen applications are derived from industrial experience and if applied to hydrogen refuelling stations are likely to put severe limitations on where they could be located in urban areas. There is a need to assess the scientific basis of the recommended distances, to see if they can be safely reduced, either because they are overly conservative or by the use of appropriate mitigation measures.
- Liquid hydrogen presents severe challenges to the materials it comes into contact with, in equipment such as pumps, vaporisers, pipework and storage vessels. It is essential that materials used are properly assessed to ensure they are compatible with the extremely low temperature of liquid hydrogen (-253°C), are resistant to hydrogen embrittlement (causing weakening of the material) and have a low permeability (passage of hydrogen through the material).
- The risks of widespread use of road tankers to supply refuelling stations with liquid hydrogen, particularly through urban areas, needs to be comprehensively assessed and compared to those currently incurred by the transport of petrol or diesel fuels. An issue for particular consideration is the control of the bulk transport of liquid hydrogen through tunnels. There is FCH JU project work looking at the above implications, namely HyTunnel, but more from the point of view of LH2 being used as a vehicle fuel rather than the bulk transportation of LH2.

6.5 Conclusions for policy makers

To fully exploit the beneficial properties of LH2, suitable standards and regulatory frameworks (RCS) will have to be established. As LH2 implies at least inter-regional, possibly international or even intercontinental transport these standards should be harmonised, ideally on an international level. Therefore, for the purposes of standardisation, the ISO/IEC framework should be further supported and used. The legal requirements with respect to quality and safety then can refer to this set of steadily updated standards.

As economies of scale are in particular important for LH2 any support for scaling up hydrogen technologies will implicitly favour the LH2 path. However, the further build-up of liquefier capacities should be accompanied by publicly supported research and development for more efficient liquefaction technologies, addressing also mid-scale applications. Although projects like PRESLHY or SH2IFT were able to close some important knowledge gaps, further pre-normative research should be supported to raise the potential of LH2 as a safe fuel, for details see concluding chapter. This research work should on one side support the standardisation efforts driven by the respective industry; and on the other hand also provide an unbiased foundation for safety-aware regulation. This will allow achieving best levels of safety in an economical way.

Considering supply infrastructures for green energy as a public task, pilot installations for storage and transport of LH2 should be installed with public support. These initial public investments could spearhead a broader roll-out of LH2. As soon as proper fossil fuel taxation and economic scales with LH2 are reached, the operation of the infrastructure can become economically attractive and may be transferred to private business. However, this LH2 market initiation should also depend on consistent and long-term stable taxation policies, best harmonised internationally.

The emerging risks posed by storage and transport of LH2 will need to be scrutinised by the regulators and policy makers and will need to cover the following areas: examination of risk assessments and research evidence, demonstration of tolerability of risk; assurance of in-depth oversight whilst maintaining a challenge function in terms of underlying assumptions made in any demonstrations; provision of a view of robustness in its risk management including Management of Change implications; and provision of a credible, authoritative view which gains public trust and acceptance. The relevant stakeholders should also be engaged within this process. In terms of emergency planning, the Seveso III requirement remains with LH2 being within scope, for co-operation by designated authorities in tests of the external emergency plan.

Public perception and engagement is pivotal to any change in technology and/ or infrastructure. Risk assessment to a suitable level, environmental assessment and reference to the availability of standards are likely to be important to demonstrate the benefits of the change. Policy makers will need early engagement in order to understand and address the key issues surrounding land use planning, refuelling stations, accidental leaks/ spills of LH2, separation distances, material compatibility, transportation, storage, etc.

The policy and legal frameworks on an international/ EU level should be coordinated to:

1. Support the development of legislation, regulations, codes and standards for the cryogenic hydrogen industry, including technical safety standards;
2. Develop/ improvise and evaluate key regulatory models to address and support hydrogen, with the aim of avoiding divergence in interpretations.
    a. Safety including emergency planning; and
    b. industry development/economy.

The ultimate aim would be to have a consistent international approach to the regulation of the (cryogenic) hydrogen sector. Existing policy, legislation, regulations and standards should be reviewed then amended, or new ones drafted in order to achieve this aim.

7 Conclusions

Liquid hydrogen is a dense, economic and safe option for storing, transporting and distributing renewable green energy. Its production requires only about 20% more energy compared to compressed gaseous hydrogen. However, this investment is largely returned by more efficient transport and distribution schemes. For LH2 based transport, as anticipated for heavy duty on short-term and in aviation in the mid-term, liquid supply infrastructure is the preferred choice, as small scale liquefaction is considered quite inefficient at the moment.

Multiple use, in particular for cooling purposes and for coupled efficient transport of electricity in superconductors, adds further value to LH_2.

Although the PRESLHY project and further pre-normative research work worldwide have provided some progress with regard to the state-of-the-art and confirmed some of the intrinsic advantages of LH_2 with respect to safety, there are still some open issues and gaps in the understanding of accidental behaviour of LH_2. The following list suggests some relevant research topics for improving further the knowledge base.

Fundamental/Modelling:

- Understand material compatibility for cryogenic hydrogen, concerning metallic and in particular non-metallic materials, and determine suitable test methodologies,
- Improve thermodynamic modelling in multiphase, non-equilibrium domain and examine reaction kinetics below 200K,
- Determine induction times and detonation cell sizes at cryogenic condition.

Dispersion phenomena:

- Develop suitable ventilation strategies for closed rooms and investigate the interaction with other mitigation technology,
- Understand multiphase effects on large scale dispersion with obstruction and/or (partial) confinement.

Combustion phenomena:

- Understand ignition phenomena under extreme weather conditions,
- Provide broader assessment of flame acceleration (FA) and deflagration-to-detonation transitions (DDT) for varying congestion and confinement in particular at large scale,
- Evaluate detonation potential of solid O_2 in LH_2 pools,
- Better understand physics and scaling of LH2 BLEVEs.

Risk assessment and mitigation strategies:

- Assessment of interaction of flame dynamics with mitigation techniques, like ventilation, water sprays flame retardant and fire extinguishing agents,
- Crash testing of vehicle tank systems,

- Integral (applied) tests (dispersion and combustion in closed rooms) for mitigation strategies, including sensor placement and performance,
- Special requirements for application in public spaces.

From the results of research work dedicated to these topics guidance and standards for the safe use of LH_2 in non-industrial settings may be iteratively improved, what will help to introduce LH_2 as the fuel of the future safely.

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